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Water Quality and Eutrophication:

the effects of sewage outfalls on waters and reefs surrounding
Stone Town, Zanzibar

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SIT Zanzibar: Coastal Ecology and Natural Resource Management
Spring 2010

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Abstract

Due to a rapid increase in Zanzibar's in population, as well as a lack of proper sewage treatment, water quality and eutrophication have become serious issues on Unguja. These issues not only threaten public health, but also threaten the health of nearby coral reefs. This study aimed to quantify the presence of fecal indicator bacteria (enterococci) and the levels of eutrophication in the surface waters of Stone Town and its vicinal reefs, while also placing results in a larger context with respect to seasonal monsoonal variations. Meetings were held with members of the Zanzibar Municipal Council, and a survey of both tourists and Zanzibaris was conducted in order to understand the public's level of awareness regarding sewage treatment and water quality. When data from bacterial enumeration was compared with recommended levels of enterococci for safe recreational waters, values revealed that Stone Town's water is unsafe for public swimming. Moreover, measured concentrations of ammonium from Chapwani Island exceeded those tolerable by healthy coral ecosystems. These results indicate that sewage pollution is causing, and will continue to cause damage to Stone Town's waters unless a new method of sewage treatment is created.

1.0 Introduction

1.1 Overview

In order to fully understand the impacts of anthropogenic pollution on the coastal waters of Stone Town and on the surrounding coral reefs, climatic patterns of the Indian Ocean and their subsequent impact on nutrient cycling must be taken into account, as seasonal variability in weather patterns directly affects concentrations of oceanic nutrients. The current distributions of oceanic and continental crust in the Indian Ocean drive large-scale climate patterns that affect weather conditions from Malaysia to the East African coast. The most notable climatic phenomenon bringing seasonal change to the waters of East Africa occurs as the Inter-Tropical Convergence Zone (ITCZ) shifts position, creating two distinct seasons, the northeast (NE) and the southeast (SE) monsoons (McClanahan 1988). Annual monsoon variability affects the nutrient conditions, sewage outfalls and storm runoff rates, as well as stratification of waters along the East African coast. Thus, knowledge of monsoonal patterns leads to a deeper understanding of the local effects of sewage pollution in coastal and coralline waters.

1.2 Indian Ocean Monsoon

Geophysical evidence shows that after the uplift of the Tibetan plateau 8 million years ago there was an abrupt change in climate, namely the strengthening of the Indian Ocean monsoon (England 1993). Due to the width and height of the Tibetan plateau, this land experiences significant seasonal changes in temperature. Conversely, because water has a very high specific heat capacity, ocean temperatures in the Indian Ocean do not vary with the same severity. Therefore, during northern hemisphere summer months, the Tibetan plateau becomes much warmer than the sea, warm air rises on the plateau, and cooler ocean air moves landward

(Fig 1a)[1]. In the winter, warm ocean air rises and cold air from the Tibetan plateau moves seaward (Fig 1b). These seasonal effects drastically change wind patterns, and as the winds change, so do the wind driven oceanic currents. Figures 2 and 3 show how the seasonal variations in ocean currents depend on the monsoonal phase. The East African Coastal Current (EACC) flows predominately northward throughout the year, but when strong winds blow southward from the Tibetan plateau during the NE monsoon, the EACC is weakened and the South Equatorial Counter Current (SECC) is formed (Fig 2). Figure 4 shows the progression of changes in currents along the East African coast and the formation of the SECC. When the SE monsoon occurs during the northern hemisphere summer, the EACC is strengthened and both currents and wind speeds reach their maximum velocities.

Moreover, changes in upwelling and downwelling of nutrient rich waters are coupled with the strengthening and weakening of the EACC. During upwelling, deep nutrient rich waters are brought to the surface, whereas during downwelling, low nutrient surface waters accumulate and prevent mixing between surface waters and deeper waters. As a result of a balance between friction and the Coriolis force, the northward flow of the EACC causes downwelling along the East African coast in the southern hemisphere. This phenomenon is responsible for bringing low nutrient waters to the coasts of Tanzania and southern Kenya. Downwelling occurs throughout the year, but is strengthened during the SE monsoon when the EACC reaches its peak velocities. Low nutrient conditions, along with warm water temperatures, are ideal for coral formation. Therefore, the oceanic and atmospheric patterns of the Indian Ocean explain the presence of high coral biodiversity in the coastal waters of Tanzania, southern Kenya, and the islands of the Zanzibar archipelago.

[1] Note: All figures are found in the appendix, starting on page iv.

1.3 Effects of Monsoon Variability on Nutrient Cycling

With a lack of nutrient input from deep oceanic waters, downwelling regions are subject to low nutrient conditions; however, they are by no means depleted of nutrients. In downwelling areas, the main nutrient sources of phosphorous are water column mixing, upwelling, river discharge, and runoff. The main sources of nitrogen are nitrogen fixation, terrestrial runoff, and upwelling (McClanahan 1988). Consequently, on the East African coast, when monsoons drastically change the precipitation rates, they also cause a significant change in nutrient concentrations. For example, Figure 5a displays the seasonal fluctuation of phosphate concentrations off the Tanzanian coast. In March, April and May, the SE monsoon brings heavy rains, which cause an increased input of phosphate from river discharge and runoff (Fig 5c) (McClanahan 1988). When lag time is accounted for, this increase in rainfall and runoff explains the peak of phosphate concentrations occurring June. Additionally, salinity levels vary seasonally, and the lowest salinity levels can be found from March to June, when rainfall and discharge are at their maximum rates. As a result of these seasonal variations in water quality caused by monsoonal cycles, it is vital to study anthropogenic pollution along the East African coast while accounting for the influences of such large-scale climate patterns.

1.4 Seasonal Variations and Sewage Pollution in Unguja

The dynamics of the Indian Ocean, and the resulting large-scale climate patterns, dictate small-scale seasonal weather variations along the East African coast. Specifically, on the island of Unguja, located just off the Tanzanian coast (Fig 6), winds blow northward during the SE monsoon and southward during the NE monsoon. When monsoon patterns change, the island experiences increased rates of precipitation, with a heavy rainy season occurring from mid

March to May and a short rainy season occurring from October to December. Additionally, the warm, shallow waters of Unguja are subject to downwelling. Thus, the area contains high levels of coral reef biodiversity, which has caused the island's economy to depend on tourism, making clean waters and health corals a necessity for any further economic development.

Nonetheless, Stone Town, the capital of Zanzibar, is a small "urban" center on a rural island in a developing country with a rapidly growing population. This has made proper city planning a nearly impossible task. The most recent census (2002) conducted by the Tanzanian government shows Zanzibar as having a population of over one million residents with a population density of 400 people/km^2 and the urban western section of Unguja as having a population of 390,074 with a density of 1,700 people/km^2. This census also states that in 2002 Zanzibar Town's population was 206,292 and had a growth rate of 4.5%. Stone Town itself represents a lesser fraction of this population; however, it is only the residents of Stone Town that are connected to the main sewage network. According to the Zanzibar Municipal Council, the fraction of Zanzibar Town with access to the sewage system represents 25% of their municipality. In addition to waste entering the ocean from those without access to the sewage system, annual averages from the Municipal Council estimate that 2,200 m^3 of liquid waste are discharged daily into the sea. In short, Zanzibar's population is exploding, and the small fraction of the island that is connected to the sewage system, is connected to a system that provides only the most basic water treatment.[2]

As a result of Stone Town's lack of proper sewage treatment, sewage pollution is damaging Zanzibar's unique coral waters. Currents in the Zanzibar channel contain two eddies and one main current that leads into deeper waters through the "great pass" (Fig 7). Eddies trap

[2] Facts and statistics from this section were gathered from the Zanzibar Municipal Council (see section 3.2) and the Tanzanian National Bureau of Statistics (www.nbs.go.tz)

pollution in the channel and prevent it from reaching deeper waters where it could be mixed within the water column. This sewage pollution not only increases rates of eutrophication, sedimentation, and coral disease, but it also poses a threat to public health.

This study hypothesized that as a result of improper sewage treatment, the placement of sewage outfalls, and oceanographic parameters in the Zanzibar channel, traces of fecal material from sewage pollution would be found in the coral waters of islands near Stone Town and levels of fecal material found in popular swimming areas would be above those recommended for safe recreational waters. Moreover, it was also predicted that water samples would have high nutrient concentrations, which would escalate with increasing proximity to Stone Town, as a result of eutrophication from sewage pollution and runoff. However, it should be noted that this study took place in April during the peak of the SE monsoon; thus, rainfall levels were high, and correspondingly, so were the rates of land runoff and sewage outflow.

2.0 Study Area

2.1 Site Selection and Location

Unguja island is located in the Zanzibar archipelago, 35 km east of mainland Tanzania at S 06° 10.0', E 039° 20.0'. Water samples were taken from four nearby reefs: Chumbe, Chapwani, Changu, and Bawe (Fig 8). Because Chumbe Island is a Marine Protected Area (MPA) and is located over 12km from Stone Town, these waters were assumed to be significantly cleaner than those near town, and Chumbe was used as a control site. Bawe, Changu, and Chapwani are popular snorkeling areas near town, and Changu also offers lodging for tourists. Five sites around Stone Town were also selected for sampling: Kizingo Landing, Africa House, Livingstone, Mercury's, and Marahubi Ruins (Fig 9). The first four sites around

Stone Town are frequented by local swimmers, and Marahubi Ruins is located in a mangrove area north of town where trash is often illegally disposed. GPS coordinates in Table 1 were used to create site maps (Figures 8 & 9).

Table 1. GPS locations of sampling sites

Site	Latitude (+/-10m)	Longitude (+/-10m)
Bawe Reef	S 06° 08.721'	E 039° 08.189'
Changu Reef	S 06° 06.856'	E 039° 09.902'
Chapwani Reef	S 06° 07.655'	E 039° 11.849'
Chumbe Reef	S 06° 16.537'	E 039° 10.497'
Kizingo Landing	S 06° 10.389'	E 039° 11.611'
Africa House	S 06° 09.895'	E 039° 11.090'
Livingstone	S 06° 09.667'	E 039° 11.255'
Mercury's	S 06° 09.503'	E 039° 11.507'
Marahubi Ruins	S 06° 08.685'	E 039° 12.455'

2.2 Sewage Dispersal in Stone Town

Currently, there are 2,289 septic tanks in Stone Town and 27 sewage outflows. Each sewage pipe extends 55m along the ocean floor from the point of low tide (Fig 10). Pipes vary in diameter from 200-600mm. Sewage is partially treated by reducing the Biological Oxygen Demand (BOD) to 60%; however, this method of treatment is very minimal and does not significantly reduce contaminants in the sewage. Sewage pipes are open continuously, regardless of the tidal time of day. The Zanzibar Municipal Council strongly advises against swimming in Stone Town, but no strong efforts are being made to educate the public about the dangers of swimming in these waters.[3]

[3] All information regarding sewage treatment and dispersal in Stone Town was gathered during interviews with Ramadhan J. Muhsin of the Zanzibar Municipal Council

3.0 Methodologies

3.1 Sampling and Data Analysis

Surface water was collected at each sampling location and transported on ice to the Institute of Marine Science (IMS). Bacterial tests were performed within six hours of sampling. Water samples were then placed in the freezer for later analysis of ammonium (NH_4) concentrations. GPS coordinates, pH, and salinity measurements were all recorded on site. Weather and tidal conditions were noted while sampling, and daily and monthly rainfall data was obtained from the Zanzibar Meteorological Department. Water from Bawe, Changu, and Chapwani was sampled three times, and water from Mercury's and Marahubi was sampled twice; however, due to time and monetary constraints, the remaining sites were only sampled once.

Enterococci (EC) bacteria were enumerated using membrane filtration, following USEPA procedures. [4] EC are found in the feces of humans and other warm-blooded animals and are often used to test for contamination of recreational waters. Studies comparing EC, fecal coliform, and total coliform counts have shown that "EC alone might be a better predictor of adverse health outcomes from exposure to fecal contamination," as they have a longer life span in marine waters than other fecal bacteria (Noble 2003). For each sample, water was filtered over a sterile membrane, and two to four replicates were done per water sample (depending on supplies available). Samples were incubated for 48 hours; afterwards, all light and dark red colonies were counted as enterococci. Numerical data was converted to cfu/100 mL (colony forming units per 100 mL). With enterococci data from Bawe, Changu, and Chapwani, single factor ANOVA tests were performed and geometric means were calculated.

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[4] See appendix page i for further detail

In order to monitor levels of eutrophication, water samples from each site were analyzed for concentrations of NH_4, following standard methods in the Intergovernmental Oceanographic Commission Manual (1993).[5] UV-visible spectrophotometry was used to test for light absorption, and data was compared with a calibration curve and blanks to determine ammonium concentration values in μM/L.

3.2 Meetings, Interviews, and Surveys

Meetings took place with Mr. Ramadhan J. Muhsin, engineering manager of the Zanzibar Municipal Council, in order to gain a deeper understanding of local sewage treatment, sewage outflow locations, the percentage of town connected to the sewage system, and future plans the Municipal Council has for modifying the current method of treatment.

Surveys of both tourists and Zanzibaris were also conducted to determine the level of water quality safety awareness in Stone Town.[6] Interviews with Zanzibaris were conducted in Swahili at popular gathering places, such as Fordhani Park or Jaw's Corner, and tourists were surveyed in English at Fordhani Park and in frequented foreigner restaurants. A total of 43 surveys were completed, 20 by tourists and 23 by Zanzibaris.

3.3 Challenges in Data Collection

If water samples had been collected five times from each site, spaced over a period of thirty days, geometric means could have been calculated according to methods of data collection utilized by the USEPA. However, due to a lack of filter paper and funding for boats, replicate water samples could not be taken from all of sites. Moreover, there was a temporary power outage in Stone Town while water samples collected on the 17th from Bawe, Changu, and

[5] See appendix ii for detailed procedure
[6] See appendix iii for sample survey sheets

Chapwani were in the incubator. The power went off three hours before the 48-hour incubation period was over.

Dissolved oxygen measurements were taken during one day of sampling, but the meter malfunctioned, so oxygen data was omitted from this study. Additionally, analysis of phosphate concentrations could not be performed due to a lack of resources at IMS.

4.0 Results

4.1 Coral Reef Water Quality

Table 2 shows results from water sampling done at Bawe, Changu, Chapwani, and Chumbe. All data was collected via analysis of coral reef surface waters. Because Bawe, Changu, and Chapwani were sampled on three different days, ANOVA tests were done with EC values to determine statistical significance. With p-values all less than 0.001, EC colony counts from Bawe, Changu, and Chapwani showed a significant statistical difference. However, when an ANOVA test was run comparing values from the three different sites over all sampling days, there was no statistical significance (p=0.15). Geometric means of EC values were also calculated (Table 3).

Table 2. Coral Reef Water Quality Data.
**BDL=Below Detectable Levels

Site Location	Date	Tidal Phase	pH	Salinity	Mean Enterococci Count (cfu/100mL)	Standard Deviation of Enterococci	Ammonium (μM/L)
Bawe	4/6	Ebb	8.13	32	8.25	1.06	0.32
Bawe	4/17	Flood	8.16	33	0.94	0.47	1.02
Bawe	4/20	Flood	8.36	32	0.42	0.14	**BDL
Changu	4/6	Ebb	8.09	32	11.00	2.83	0.12
Changu	4/17	Flood	8.23	33	1.56	0.63	0.25
Changu	4/20	Flood	8.22	32	8.83	0.88	0.12
Chapwani	4/6	Ebb	8.14	31	5.25	1.77	2.18
Chapwani	4/17	Flood	8.20	33	2.69	0.77	0.68
Chapwani	4/20	Flood	8.21	32	0.92	0.14	0.83
Chumbe	4/12	Ebb	8.10	32	4.15	1.49	**BDL

Ammonium concentrations were below detectable levels (BDL) at Chumbe and during one sampling day at Bawe (4/20). Table 3 shows the average ammonium concentrations for Bawe, Changu, and Chapwani. Chumbe is located furthest from Stone Town, followed by Bawe, Changu, and Chapwani respectively; therefore, ammonium concentrations increased with increasing proximity to Stone Town, as hypothesized.

Table 3. Enterococci p-values and geometric means, averge ammonium concentrations

	EC p-value	EC Geometric Mean (cfu/100mL)	Average Ammonium Concentration (μM/L)
Bawe	3.27E-06	1.48	0.45
Changu	0.000595	5.33	0.16
Chapwani	0.000125	2.35	1.23

4.2 Stone Town Water Quality

Table 4 shows data collected from sites in the Stone Town area. Water samples taken on the 15th had significantly higher levels of EC than those of the 8th. This is most likely a result of heavy rainstorms which occurred on the 13th and 14th. Samples were marked as too numerous to count (TNC) if there were over 1500 cfu/100mL. Therefore, Marahubi showed at least a 34-fold increase in cfu/100mL and Mercury's had at least a 17-fold increase after the rains. Image "c" on page "i" of the appendix shows an example of a plate considered TNC. The outer ring of the plate has dark, well-developed colonies, whereas central colonies are pale and small, illustrating that only colonies on the outer edges had enough room to grow. Consequently, it is assumed that cfu/100mL values would have been higher, had more room been available for the colonies to develop. Based on rough estimations, actual cfu/100mL values could have been higher than 2000cfu/100mL for some samples. Of all water samples collected, those collected at Mercury's and Marahubi on the 15th had the highest EC values, as well as the highest concentrations of ammonium. However, Livingstone had a relatively high enterococci count and a BDL of ammonium, suggesting that there is no clear correlation between EC and ammonium values.

Table 4. Stone Town Water Quality Data
*TNC=Too Numberous to Count, **BDL=Below Detectable Levels

Site Location	Date	Tidal Phase	pH	Salinity	Mean Enterococci Count (cfu/100mL)	Standard Deviation of Enterococci	Ammonium (μM/L)
Marahubi	4/8	Ebb	8.52	33	43	4.24	0.7736975
Marahubi	4/15	Flood	8.21	32	*TNC	-	0.9542065
Mercury's	4/8	Ebb	8.09	34	84.5	0.71	0.0516615
Mercury's	4/15	Flood	8.16	32	*TNC	-	1.302331
Kizingo	4/15	Flood	8.29	32	140.5	22.65	0.348212
Africa House	4/15	Flood	8.19	33	377.5	58.93	0.3095315
Livingstone	4/15	Flood	8.16	33	456	5.42	**BDL

4.3 Annual and Monthly Rainfall Data

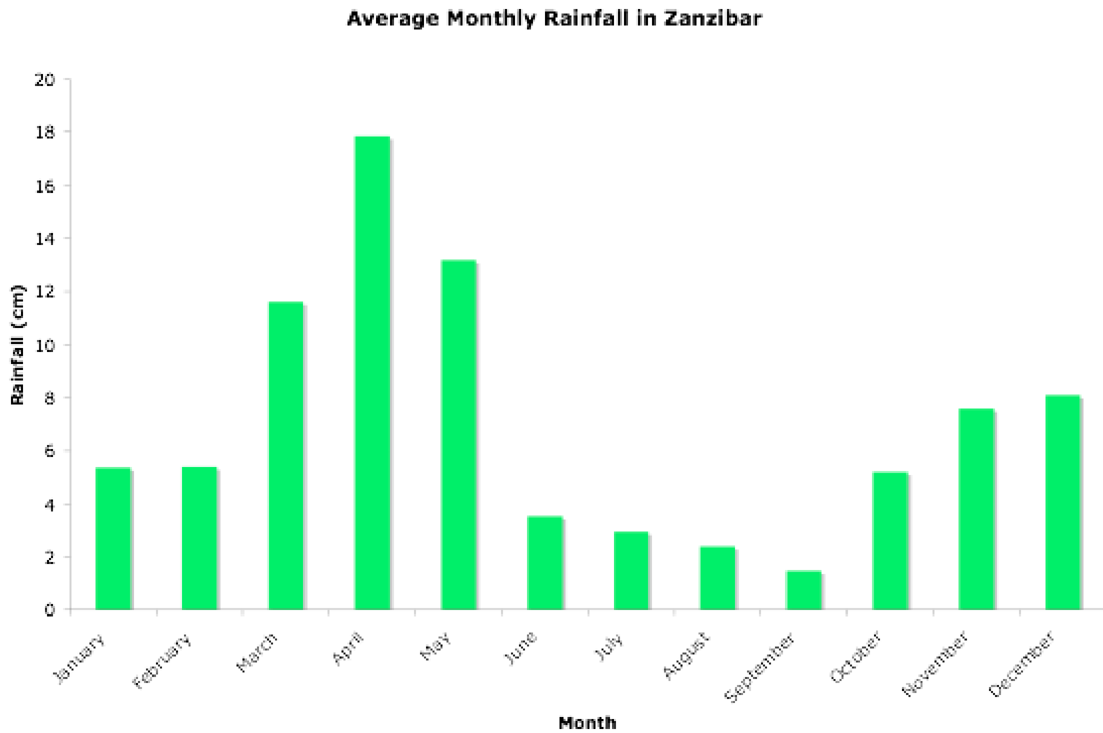
Table 5 and Graph 2 show precipitation data recorded by the Zanzibar Meteorological Department during time of this study.[7] The maximum value recorded occurred on the 15th (35.2mm), and the total sum of precipitation is 153.1mm. These values are consistent with data shown in Graph 1, where April has a monthly rainfall average of approximately 17.7 cm (177mm). Graph 1 also illustrates the drastic seasonal changes that occur as a result of monsoonal variations. As a result of precipitation induced by the SE monsoon, Zanzibar receives 49% of its annual rainfall during March, April, and May.

Table 5. Rainfall data for Zanzibar, April 2010 from the Zanzibar Meterological Department. Note: Sampling dates are bold and italicized

Date	Rainfall (mm)
4/1	5.6
4/2	19.7
4/3	0.0
4/4	16.6
4/5	13.0
4/6	***3.2***
4/7	1.6
4/8	***0.2***
4/9	0.5
4/10	0.0
4/11	3.3
4/12	***0.0***
4/13	0.0
4/14	19.9
4/15	***35.2***
4/16	12.1
4/17	***0.1***
4/18	0.0
4/19	0.0
4/20	***0.0***
4/21	6.2
4/22	0.0
4/23	9.2
4/24	0.0
4/25	0.0
4/26	2.6
4/27	4.0

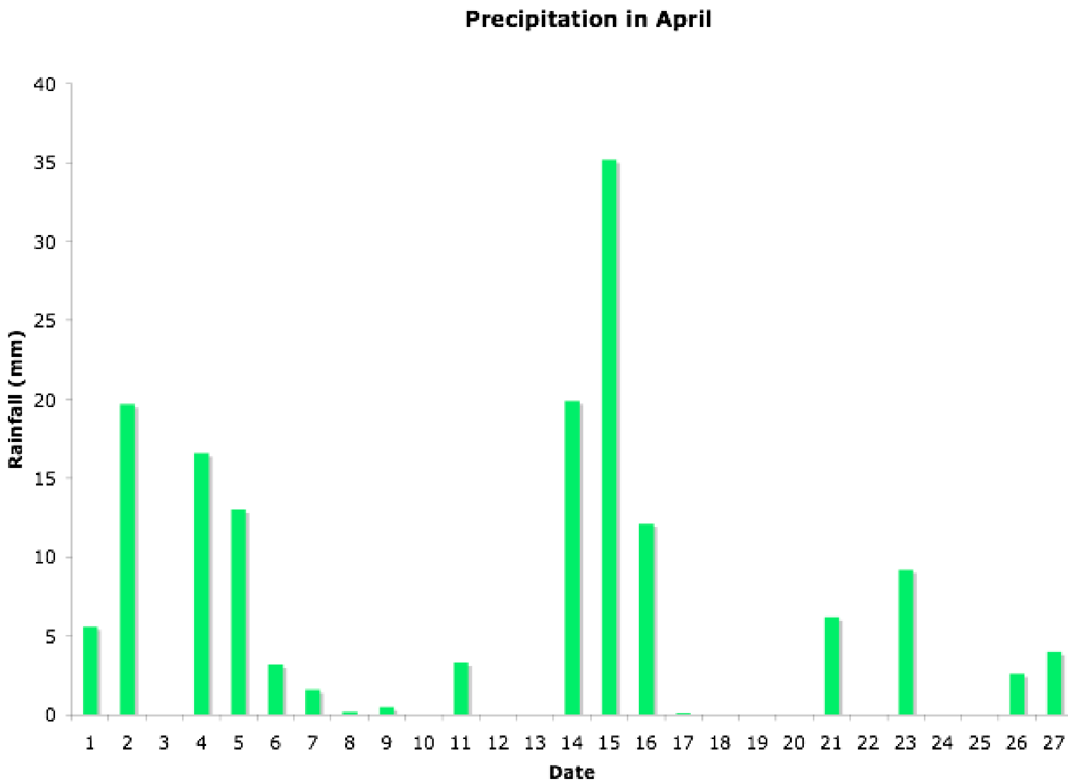
[7] Note: Rainfall data stops on the 27th because further data was not yet available. This study was completed on the 28th of April.

Graph 1. Rainfall data taken from MSN weather.



Throughout the time period of sampling for this study, the heaviest rainfall occurred from the 14th to 16th. The sum of precipitation recorded during these three days is 67.2 mm, which is 44% of all rainfall recorded during April. Correspondingly, the highest values of enterococci found in this study were from waters sampled on the 15th (Table 4). The second highest recordings of precipitation over a period of consecutive days occurred from the 4th to the 5th. Rainfall totaled 29.6 mm (19% of monthly rainfall). Reef waters sampled on the 6th from Bawe, Changu, and Chapwani had higher enterococci counts than on any other day of reef sampling (Table 2). These results indicate that there is a clear correlation between sewage outflow, enterococci, and rainfall.

Graph 2. Precipitation data from the Zanzibar Meteorological Department



4.4 Public Survey and Interview Statistics

Of the 23 Zanzibaris interviewed, only 5 were aware that it is unadvisable to swim in the waters of Stone Town. Although most interviewees acknowledged that sewage goes into the ocean and also understood that sewage is dangerous for public health and the environment, 10 of the 11 males interviewed and 1 female (<10 years old) claimed to swim frequently in town.[8] If an interviewee responded "yes" to swimming in town, was aware that sewage goes into the ocean, and recognized that sewage can lead to

Table 6. Statistics from survey of locals

Zanzibari Survey	
Average Age	30
Average Years of Schooling	10.36
Female	12
Male	11
Swims in town	48%
Has been told it is unadvisable to swim in town	22%
Aware that sewage goes into ocean	83%
Thinks sewage is bad for health	91%
Thinks sewage is bad for environment	100%

[8] Note- As a result of the Islamic culture of Zanzibar, only one female (<10 years old) responded "yes" to swimming in town. It is considered indecent for women to swim publicly with men, so must women go outside of town if they want to swim.

health problems, they were asked why they continue swim in polluted waters. Answers included the following:

- The tide takes the pollution far out to sea
- Bacteria die in salt water
- There is a lot of water and just a little pollution, so it is safe
- You need to enjoy the present and not worry about the future
- The ocean cannot be polluted, it will always be clean
- It costs money to go elsewhere to swim
- Peer pressure

Of the 20 tourists interviewed, 13 had not been informed that is dangerous to swim in the waters around town; those who had been informed were told by friends, guidebooks, and signs in hotels. All of the tourist interviewees who had gone swimming (or were planning to go swimming) in Zanzibar said they went (or would go) to locations outside of town. Swimming locations included the following: Paje, Prison Island, Nungwi, Mtoni, Bububu, Breezes Beach Resort, Mbweni, and various scuba diving trips. Although many tourists were unaware that Stone Town lacks a proper sewage treatment system, based on the amount of trash they had seen in streets and on beaches, many speculated that a problem exists. Additionally, 10 of the 20 tourist interviewees said that they would be more likely to return to Stone Town if the waters were cleaner and safe for swimming.

Table 7. Statistics from surveys with tourists

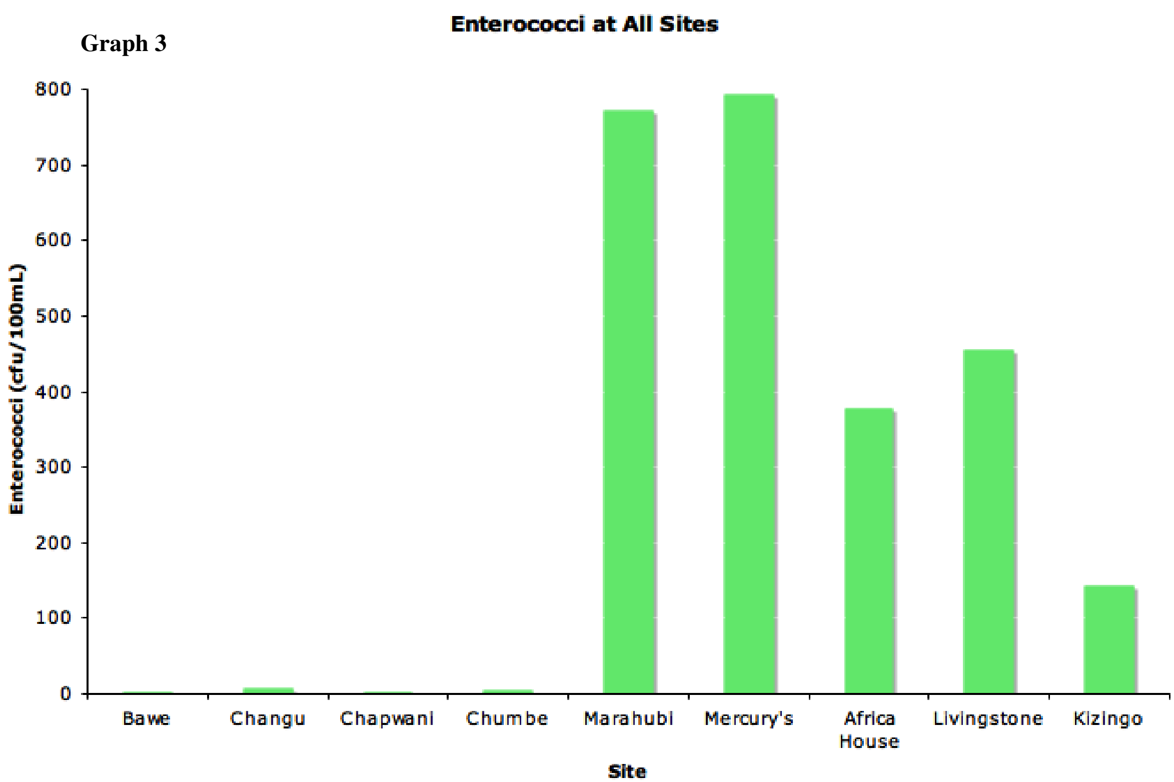
Tourist Survey	
Average Age	26.7
Female	13
Male	7
Aware of Sewage Issues	40%
Have been told not to swim in town	35%
More likey to return to Stone Town if waters were cleaner	50%

5.0 Discussion

5.1 Enterococci and Ocean Circulation Patterns

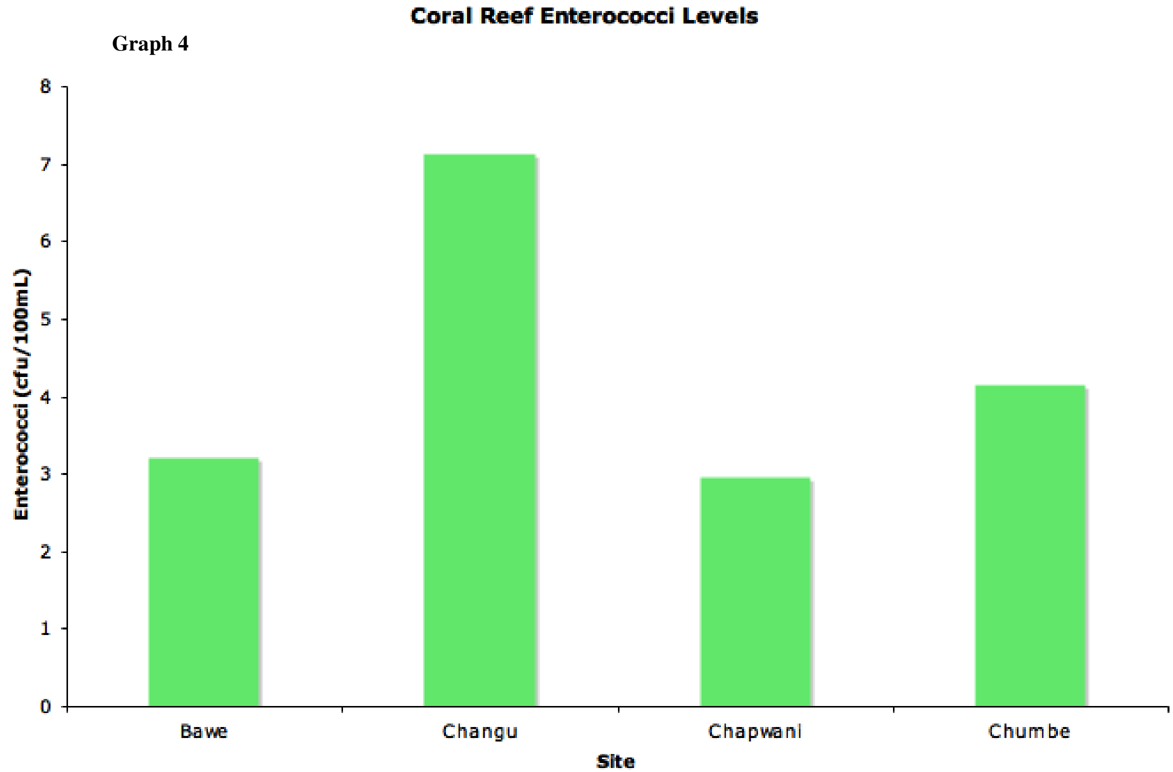
The numbers of enterococci enumerated in this study offer concrete evidence that a serious water quality problem exits in Stone Town. Furthermore, observed distributions and variations in EC values can likely be explained by monsoonal weather patterns and local oceanographic conditions in the Zanzibar channel. Figure 10 shows that sewage outfalls are placed uniformly along the coast; however, data from this study reveals that the sewage is not evenly dispersed throughout the waters. Water in the northern part of Stone Town has poor circulation, especially in the bay areas on either side of the harbor (Fig 7). Samples from these areas (Marahubi & Mercury's) had the highest counts of EC (Graph 3). Of the sites sampled in

Graph 3

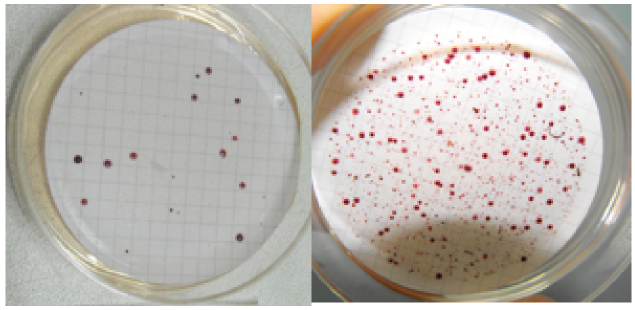


Stone Town, Kizingo had the lowest EC values, which is most likely a result of its location in the southern part of town, where currents flow northward towards the “great pass.”

Moreover, eddies in the Zanzibar Channel prevent Stone Town’s pollution from circulating into deeper waters. Contrary to the hypothesized trend that EC values would decrease with increasing distance from town, of the three reef sites sampled around Stone Town, Changu had the highest average counts of EC and the highest geometric mean (Table 3). This can be explained by oceanographic factors, as current circulations in Figure 7 show that eddies might be causing polluted waters to re-circulate and linger near the island. Additionally, Changu has some accommodations for tourists, which would increase the amount of anthropogenic pollution found in the island’s waters. With respect to Chumbe, the control site, sampling was only done once; therefore, it is difficult to assess the significance of its EC values. Because Chumbe is a Marine Protected Area (MPA), surface water sampling done at Chumbe was predicted to be “pristine.” However, the amount of EC found at Chumbe was higher than expected. Although the counts of EC from first day of sampling (4/6) at Bawe, Changu, and Chapwani exceeded values from Chumbe (Table 1), EC values from the second and third days of sampling were much lower than those of Chumbe. The high EC values found from sampling on the 6th at Bawe, Changu, and Chapwani can be explained by high levels of precipitation on the 4th and 5th. Although some rainfall occurred before sampling at Chumbe, the amount of precipitation on the 11th was only 3.3mm, whereas rainfall from the 4th and 5th totaled 29.6mm (Table 1 & Graph 2). Consequently, replications are needed in order to determine the normal range of EC values in waters over Chumbe’s protected reef.



Furthermore, sites that were sampled more than once (Bawe, Changu, Chapwani, Marahubi, and Mercury's) all showed statistical significance in EC enumeration. These differences are likely a result of changes in weather patterns. Sampling for this study was conducted during April, when monsoon winds bring heavy rain. During monsoonal rains, the East African coastal waters experience an elevated input of freshwater via runoff. Because garbage is found in high concentrations on the streets of Stone Town, farming on the island makes use of fertilizer and harmful chemicals, and sewers can overflow during heavy rains, levels of eutrophication and indicator bacteria are amplified during the rainy season. For example, sampling at Mercury's and Marahubi was done twice, and the second date of sampling occurred after three days of heavy rain (Graph 2). The image below shows two Petri dishes with samples from different dates. For both dishes, 50mL of water were filtered from Marahubi Ruins. This extreme increase in EC colonies shows the importance of accounting for seasonal fluctuations when monitoring water quality and planning sewage systems.



(a) (b)

Marahubi results before (a) and after (b) the heavy rains

5.2 Enterococci and Water Quality

Previous water quality studies done in Zanzibar have relied on measuring fecal coliform or nutrient concentrations, in order to determine the extent of sewage pollution and the safety of recreational waters. However, studies comparing various indicator bacteria, such as coliform, *E.coli* (Type I) and EC (Fig 11), have shown that EC are “least affected by concentration of sea water and no growth phase was observed regardless of concentration of seawater, [and therefore, it] may be the best indicator of recent enteric pollution in seawater” (Hanes 1967). Consequently, in 2004 the USEPA replaced the use of fecal coliform testing with that of enterococci, in order to more accurately determine the water quality of public beaches. Although regulations vary between states in the US, the USEPA places cutpoints at 35 and 104 cfu/100mL, such that anything between 35 and 104 cfu/100mL is dangerous for swimmers and anything above 104 cfu/100mL is extremely dangerous. Because all EC counts from sites in Stone Town were above 35 cfu/100mL and all averages were above 104 cfu/100mL, results from this study clearly indicate that the waters around Stone Town are unsafe for swimming. Yet, during sampling in town, swimmers could be seen at every site (Graph 3 & Table 4).

Health problems associated with swimming in waters with high levels of fecal bacteria include gastrointestinal illness and respiratory disease. According to Cabelli et al., swimmers reporting either vomiting, diarrhea and fever, or stomach pain and fever have highly credible gastrointestinal illness, and those reporting fever and nasal congestion, fever and sore throat, or coughing with phlegm have significant respiratory disease (1982). A study done by Haile et al. observed a significant risk of skin rash in swimmers when EC values in waters exceeded 104 cfu/100 mL, as well as an increased risk of nausea, vomiting, diarrhea with blood, and gastrointestinal illness (1999). In Stone Town, the lowest numbers of enterococci recorded for this study were from before the rains (43 cfu/100mL, Marahubi), and the lowest value found after the rain was 140.5 cfu/100mL (Kizingo)[9]. These results confirm that Stone Town's waters contain concentrations of fecal bacteria above acceptable recreational water quality limits, which poses a threat not only to public health, but also to the health of nearby coral reefs.

5.3 Eutrophication and Ammonium

Concentrations of ammonium in this study were monitored in order to assess the levels of eutrophication around Stone Town and in vicinal reefs. Of the reefs sampled, Chapwani had the highest average concentration of ammonium, which is likely a result of its proximity to town. Moreover, consistent with the hypothesis that Chumbe should have the best water quality among the sites, ammonium in Chumbe's waters was below detectable levels. Of the sites sampled in Stone Town, Mercury's and Marahubi Ruins had the highest concentrations of ammonium. This corresponds with the high levels of EC and poor water circulation found at these sites. However, it is difficult to assess the extent of eutrophication using ammonium concentrations alone, since dissolved nitrogen in marine waters exists in several forms, including ammonium and nitrate. Bacteria convert nitrate to ammonium when oxygen levels are low, and therefore, when ammonium levels are high, nitrate levels are often low (and vice versa). Additionally, a previous study done in Zanzibar monitoring levels of ammonium, nitrate, and phosphate at Bawe,

[9] Note: Kizingo was not sampled before the rain. Only Marahubi and Mercury's were sampled prior to the rains.

Changu, Chapwani, and Stone Town revealed that "phosphate, but not ammonia or nitrate, has an inhibitory effect on both the growth rate and the calcification rate of coralline algae…[indicating] that phosphate can be partly responsible for the observed decrease of coralline algae cover outside Zanzibar Town" (Bjork 1995). Thus, closer nutrient monitoring is necessary to fully assess water quality.

However, ammonium concentrations found in this study do provide insight into the state of eutrophication in reefs near Stone Town. Studies done in the Caribbean and Great Barrier Reef have established that nitrogen levels should not exceed 1.0 μM/L in order to maintain healthy reefs (Goreau et al. 1994). While total nitrate levels were not measured in this study, results show that some water samples have exceeded these concentrations with ammonium values alone. The average ammonium concentration for Chapwani's reef was 1.23 μM/L. These elevated levels are further supported by observations made while sampling. Based solely on subjective visual studies made while snorkeling during sample collection, Chumbe was the healthiest reef, followed by Bawe, Changu, and Chapwani respectively. Chapwani's reef was overgrown with algae and sea urchins were abundant. This reflects poorly on the reef's health, as "eutrophicated reef areas often become dominated by a few fast-growing species of noncalcareous macroalgae" (Bjork 1995), and urchins indicate fishing pressure (Tyler 2005). Sea turtles were seen at Chumbe and Bawe, as well as high levels of coral diversity; however, Chumbe's reef appeared significantly healthier than that of Bawe. This observation is supported by numerical data, as Bawe had an ammonium concentration of 0.45 μM/L and Chumbe's concentrations were undetectable. Similar to Chapwani, Changu's reef also had high numbers of urchins, seaweed, and algae, but surprisingly, Changu's ammonium concentrations were lower than those of Bawe. The discrepancy suggests that ammonium testing alone is not enough to assess water quality, and other parameters, such as concentrations of phosphate and nitrate, need to be measured.

5.4 Hidden Impacts of Sewage on Coral Reefs

Despite the fact that reef measurements of enterococci and ammonium were much lower than those recorded in Stone Town, and enterococci levels were far below the 35cfu/100mL cutoff for safe recreational waters, more consideration needs to be given to the effects of anthropogenic pollution on coral reef health. Recent studies done in the Florida Keys by Lipp et al. have shown that coral surface microlayers (CSM) can be used to monitor the impacts of sewage on reefs and “bacteria may be chemotactically attracted to [coral] mucus” (Ducklow 1979). Because fecal indicator bacteria are “subject to a high degree of die-off and dilution in tropical marine waters, particularly in offshore areas such as coral reefs,” it is difficult to assess the damage done to reefs from runoff and sewage pollution using surface water sampling alone (Lipp et al. 2004). Results from Lipp et al.’s study revealed an increased detection rate of both indicator bacteria and human enteroviruses in CSM relative to the overlying water column. Some samples in their study varied as much as having 75 cfu/100mL EC in surface waters and 300cfu/100mL EC in the coral mucus layer. Moreover, human enteroviruses were not detected in any of their surface water samples but were found in CSM from all sites.

In addition to causing a decrease in coral reef water quality, sewage outflows and runoff also damage corals by promoting sedimentation. Sediments released into water increase turbidity and decrease the amount of sunlight available for zooxanthellae, the symbiotic photosynthetic algae found in coral polyps (Gillion 2009). When sediment lands on corals, polyps must divert energy from their metabolic processes in order to reject sediment through one of the following four processes: “polyp distension by uptake of water through the stomodeum, tentacular movements, ciliary action, and mucus production” (Pastorok 1985). However, a polyp’s ability to successfully reject sediment is dependent on the rate of sedimentation, as well as the species of coral. When sedimentation rates exceed a coral's tolerance level, coral growth is retarded, and eventually, all or part of the coral colony will die. Ultimately, this causes a shift in species abundance dependent on coral tolerance levels (Pastorok 1985).

As a result of the effects of sewage on CMS and sedimentation rates, it is premature to say that this study of water quality in Stone Town provides a thorough assessment of the impacts of sewage on nearby reefs. It is very probable that surveying reef species and sampling CSM for fecal indicator bacteria and human enteroviruses would provide much more information about the health of the reefs of Bawe, Changu, Chapwani, and Chumbe, as well as how to better preserve these diverse ecosystems.

5.5 Seasonality in East African Coastal Waters

Because the annual transitions between NE and SE monsoon drastically affect local climate along the East African coast, it is important to place results from this study in a larger context. Figures 5 a –d show monthly variations in phosphate, salinity, river discharge, and nitrate levels. Phosphate, salinity, and nitrate concentrations were recorded off the Tanzanian coast, and river discharge was recorded in the Kenyan rivers Tana and Sabaki. Figure 5c shows that river discharge rates are highest in April (SE monsoon), when the heaviest rainfall occurs. As a result of increased runoff, river discharge, and rains, salinity values are also lowest in April. However, salinity values found in this study were lower than expected. Coral waters sampled had an average value of 32 ppt, yet corals require water with salinity values between 33-36 for healthy growth (Coral 2006). McClanahan's study (Fig 5b) showed April as having an average salinity of approximately 34.2 ppt (1988). This discrepancy could be a result of how and when waters were sampled during this study, the accuracy and calibration of the equipment, and human error. Surface waters were used to measure salinity in this study, but because heavy rains can cause a thin layer of fresh water to form on the surface of waters, it is possible that salinity values might have been slightly greater further down within the water column. Moreover, the hand refractometer used from IMS to record salinity was difficult to calibrate and had a human error of approximately +/- 1ppt. After accounting for error, it is possible that salinity averages were between 33 and 34 ppt, which would provide an accurate reflection of the low salinity values induced by the SE monsoon.

Likewise, nitrate and ammonium values fluctuate with the SE and NE monsoons. During NE monsoon when waters are calmer and the thermocline is more stable, nitrogen fixing blue-green algae have optimum growing conditions (McClanahan 1988). This is illustrated in Figure 5c, where nitrate levels peak from December to February. When nitrate levels are low, ammonium values are often high. Therefore, since increased rates of runoff, sewage outflow, and river discharge decrease oxygen levels and cause bacteria to convert nitrate to ammonium, East African coastal waters should have higher levels of ammonium during the SE monsoon.

In addition, it is likely that values of EC in the surface waters of Stone Town fluctuate with monsoon induced weather patterns. Because this study was done during the SE monsoon, when rainfall, runoff, and sewage outflow rates are expected to be at their maximum values, it is predicted that EC levels might be lower during the NE monsoon. Nonetheless, it is also possible that the calmer waters of the NE monsoon would result in less surface water mixing and cause an increase in the amount of EC. Therefore, because no prior studies of enterococci have been done in Stone Town's waters, an annual study should be conducted to determine how enterococci concentrations fluctuate between NE and SE monsoons, in order to establish the best means of improving the city's sewage system.

5.6 Stone Town's Sewage System and Public Awareness

Currently, sewage is being released continuously into the ocean with no consideration for tidal or seasonal monsoonal variations. If sewage outlets had been designed and positioned more strategically, the dispersion of sewage into the open ocean could have been maximized such that sewage outflows were directed towards the "great pass." The Zanzibar Municipal Council is conducting a feasibility study of building a sewage treatment plant and/or creating a long, central line to direct all of the pollution farther out to sea, which would replace the many small outlets that are found along the coast of Stone Town. Unfortunately, there is no government funding for such a project, and funds are being sought from coral conservation groups and the World Bank.

Moreover, results from surveying Zanzibaris in Stone Town reveal that there is little public concern about water quality safety, little enforcement from the local government, and thus, little public pressure to change. The Municipal Council advises against swimming around Stone Town and has prohibited swimming in certain areas, yet only 22% of local interviewees were aware that swimming in town not advised. Most interviewees knew that sewage enters the ocean without treatment and that it is a health hazard, but few of the Zanzibaris surveyed recognized that it is dangerous to swim in the waters around town. All of the men interviewed, except one, swim frequently in the ocean and have no concerns about adverse health effects. This misconception stems from a lack of information and understanding. Responses from the survey indicate that the local attitude towards pollution is one in which humans cannot have a significant impact on their environment. Many interviewees claimed that the ocean could not be polluted because it is so vast and the input of waste is small in comparison. This attitude is further displayed in the streets of Stone Town, where piles of garbage can be found down every alley. However, if no one is aware that swimming is unadvisable in Stone Town due to high levels of fecal contamination, it is impossible to expect the public's understanding of environmental issues to change. Therefore, it is essential that public awareness develop in Stone

Town, as the island's economy depends on tourism, and without clean waters and spectacular reefs, the island will quickly lose its appeal.

6.0 Conclusion

As cities like Stone Town continue to experience rapid development and population growth, finding practical solutions to deal with water quality and sewage pollution is vital. Although building a new sewage treatment plant would be an expensive project, it is in the best interest of Zanzibar to properly manage its waste. Levels of enterococci presented in this study unquestionably indicate that the current system of sewage management and waste disposal is having a detrimental effect on the waters surrounding Stone Town. Not only will proper sewage treatment improve public health, but it will also help to protect coral reefs, which will in turn help the economy of Zanzibar by increasing tourism. Research and data analysis from this study demonstrate that managing waste disposal is not a simple problem and that seasonal changes in weather and oceanographic patterns must be taken into account. By studying the natural fluctuations in nutrient concentrations due to changes in monsoonal periods, variations in pollution circulation and distribution can be better understood. Furthermore, any change to the current sewage treatment system will not occur without an increase in public awareness and support. Without public pressure to develop a better method of sewage treatment, there is little incentive for anything to be accomplished in a timely manner.

7.0 Recommendations

Future studies should aim to do a more comprehensive analysis of how sewage outfalls are dispersing nutrients, indicator bacteria, and human enteroviruses in Stone Town's coastal waters. Monitoring more nutrient levels (i.e. phosphate, nitrite, ammonium, and dissolved oxygen) would provide deeper insight into the extent of eutrophication. Moreover, replication of enterococci procedures should be performed, in order to determine how values fluctuate with tidal and monsoonal changes. It would be particularly useful and interesting to determine the safest conditions for swimming with respect to the level of enterococci, rainfall, and tidal time of day. In addition to sampling surface waters, coral mucus layers should be analyzed for enterococci and enteroviruses, so that coral reef health can be more thoroughly assessed.

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